Project ID: mat221

Lightweight and Highly-Efficient Engines Through Al and Si Alloying of Martensitic Materials

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2021 DOE Vehicle Technologies Office Annual Merit Review
June 23, 2021

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Timeline/Budget

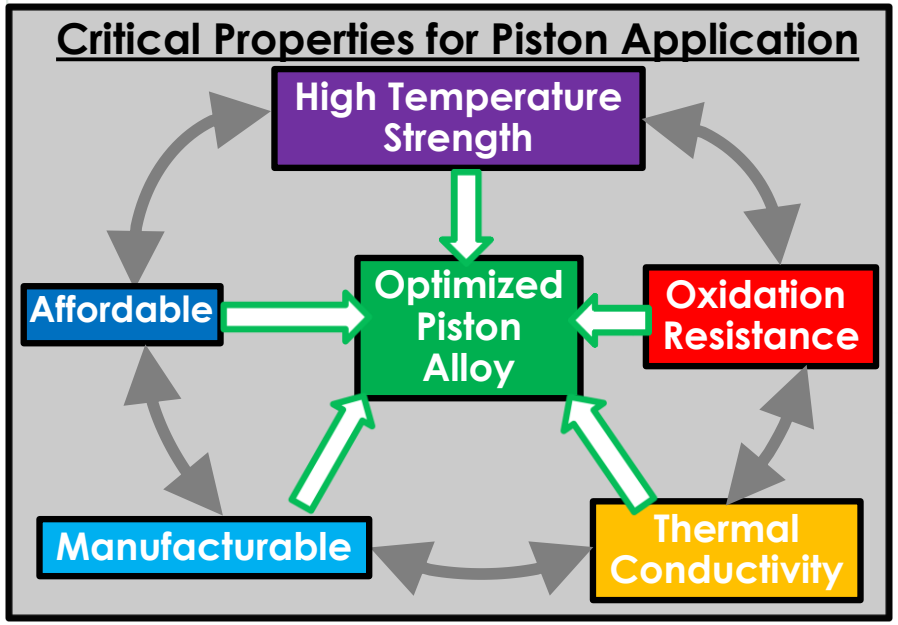
- DOE Budget: $625k/3 yrs
- Industry cost share: $580K/3 yrs
- Program Start: May 2019
- Program End: April 2022
- 66% Complete
- Originally a 2 year timeline, but 1 year extension granted in April 2021.

Partner

- Cummins

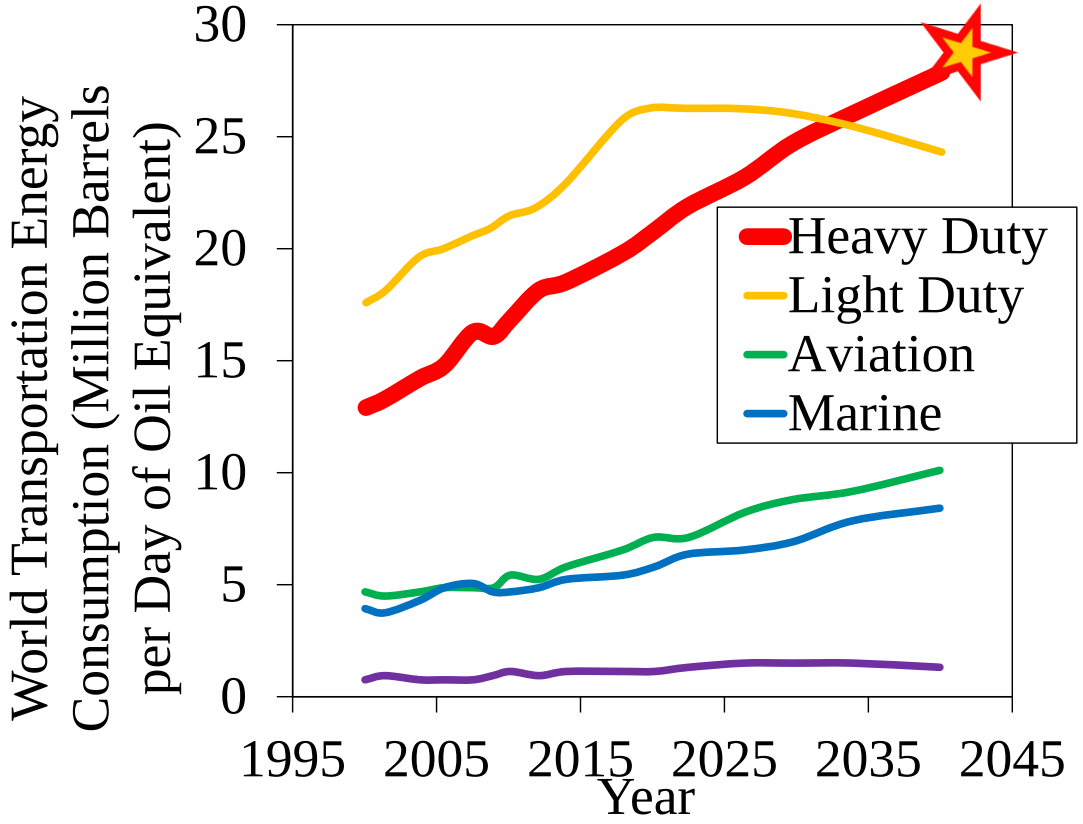
Barriers

- Optimization of **elevated temperature strength, thermal conductivity, and oxidation resistance** of piston steels
- Machinability/weldability/Affordability
- Scaling steel to larger sizes
- Engine downsizing

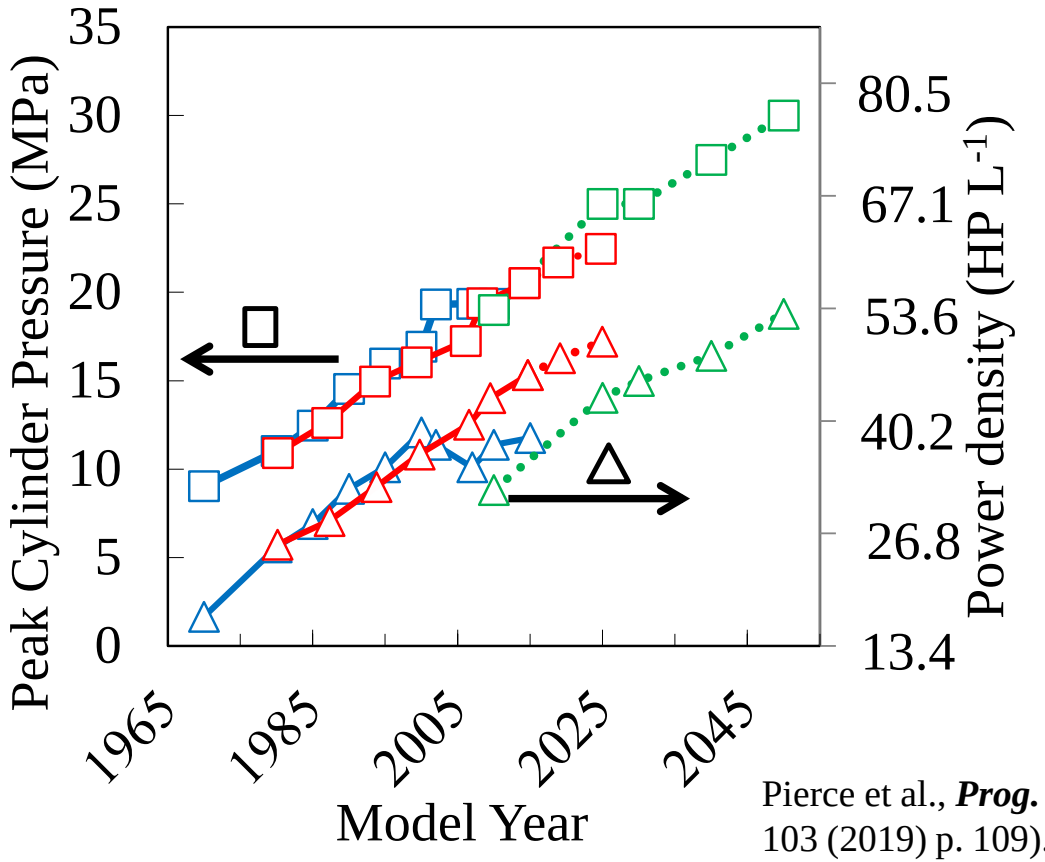


Relevance

- Higher cylinder pressures and temperatures = higher efficiency.
- Current heavy duty diesel (HDD) piston steels (4140 & micro alloyed steel (MAS)) not suitable for temperatures ≥~500°C.
- Challenge to electrify heavy duty long haul freight due to battery power density
- Objective: develop affordable, innovative, higher temperature piston alloys



Exxon Mobil. 2018 outlook for energy: a view to 2040; 2017

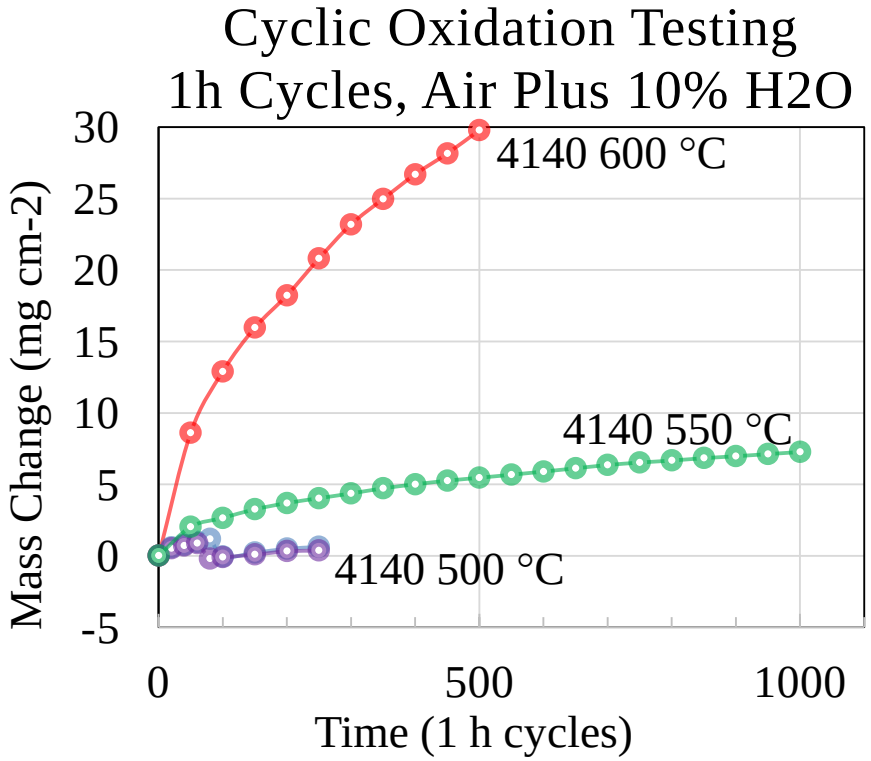


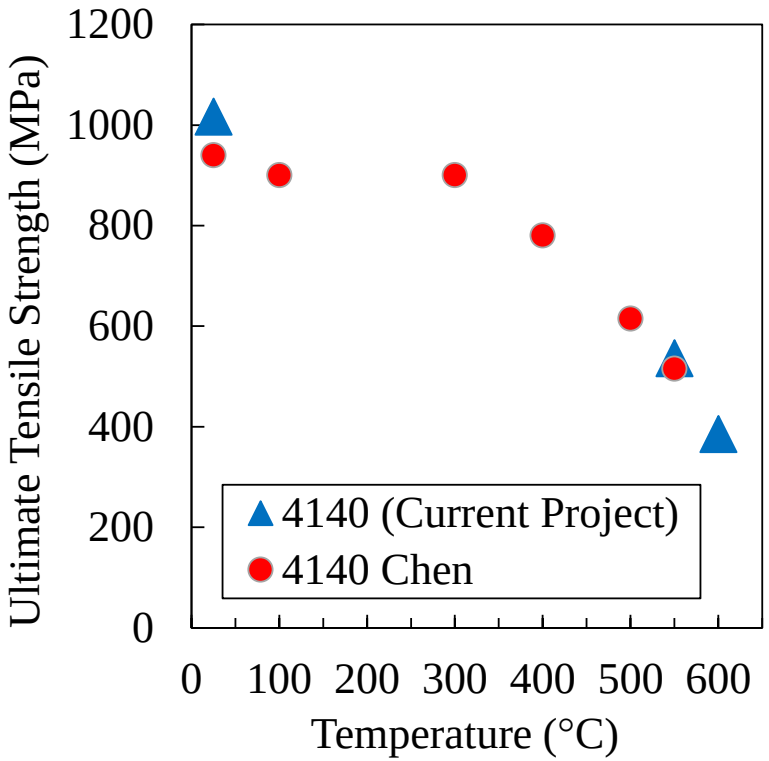
Pierce et al., ***Prog. Mat. Sci.*** 103 (2019) p. 109).

4140 is Currently at Limits of Temperature and Strength in Heavy Duty Diesel Engines (HDDE)

- Alloy 4140 is current state of art for HD pistons (low alloy steel).
- 4140 is limited to peak temperatures near 500 °C (oxidation and strength concerns).
- Limits of 4140 pistons are a major barrier to increase engine efficiency.
- Challenge to modify 4140 and significantly improve properties, at low cost

Composition (wt.%)						
Alloy	Mn	C	**Cr**	Si	Mo	Fe
4140	0.9	0.4	**1**	0.3	0.2	97.6





Milestones

- Milestones contain details not authorized for public release.

Alloy Development to Piston Prototype and Engine Test

Lab Scale Research Years 1 and 2

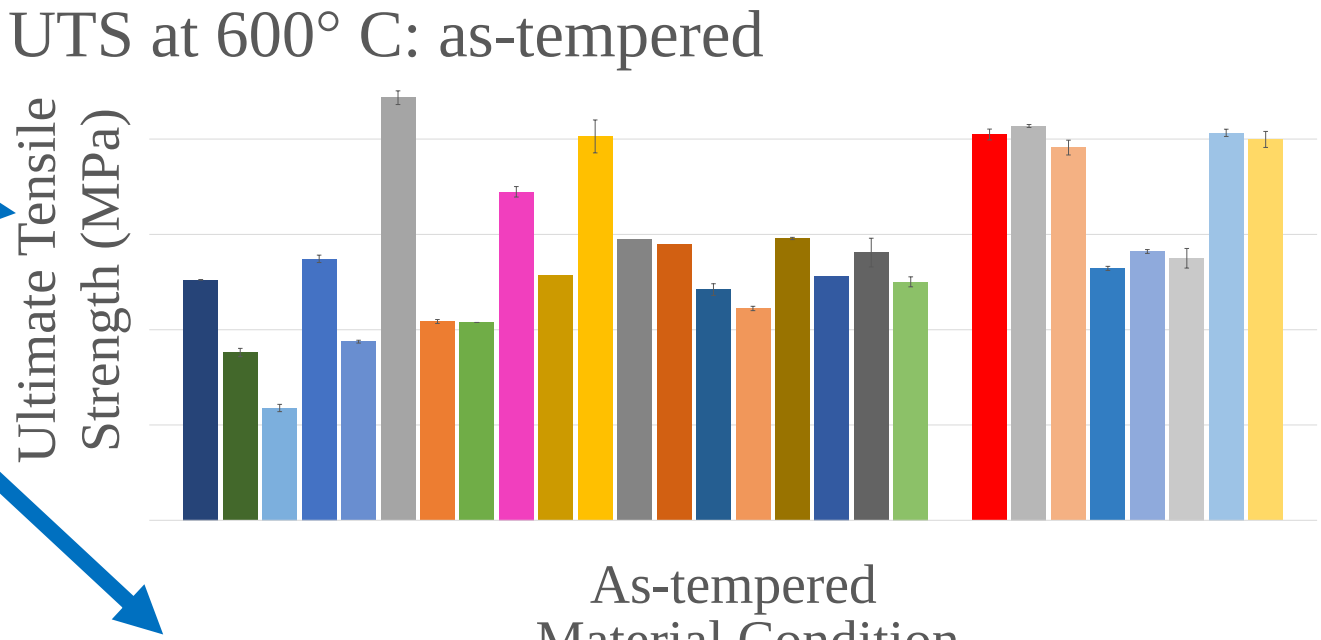
- Computationally designed ~35 different alloy compositions
- Arc melted lab scale heats
- Thermo-mechanically processed
- Performed processing and evaluations
  - Compositional measurement
  - Elevated temperature tensile and fatigue testing
  - Cyclic oxidation testing at 550 and 600 °C in
  - Thermal properties: Diffusivity, heat capacity, CTE
  - Computational fluid dynamics analysis

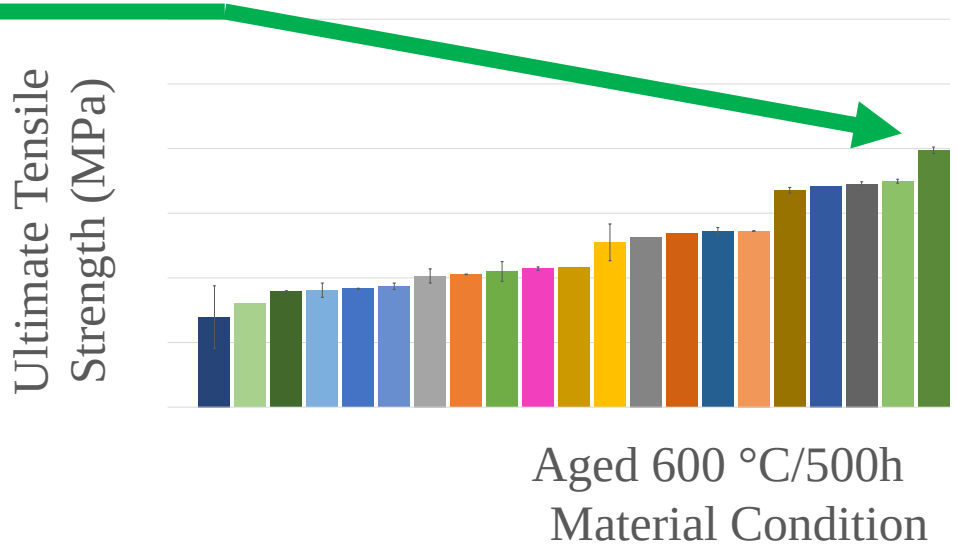
Industrial Scale Up Year 3

- Down selected promising alloy
- In process of scaling up alloy (1500 lbs heat)
- In process of manufacturing prototype pistons
- **Engine testing of New Alloy Planned for FY2022**

Novel Alloy Design Leads to Exceptional Strength at 600°C

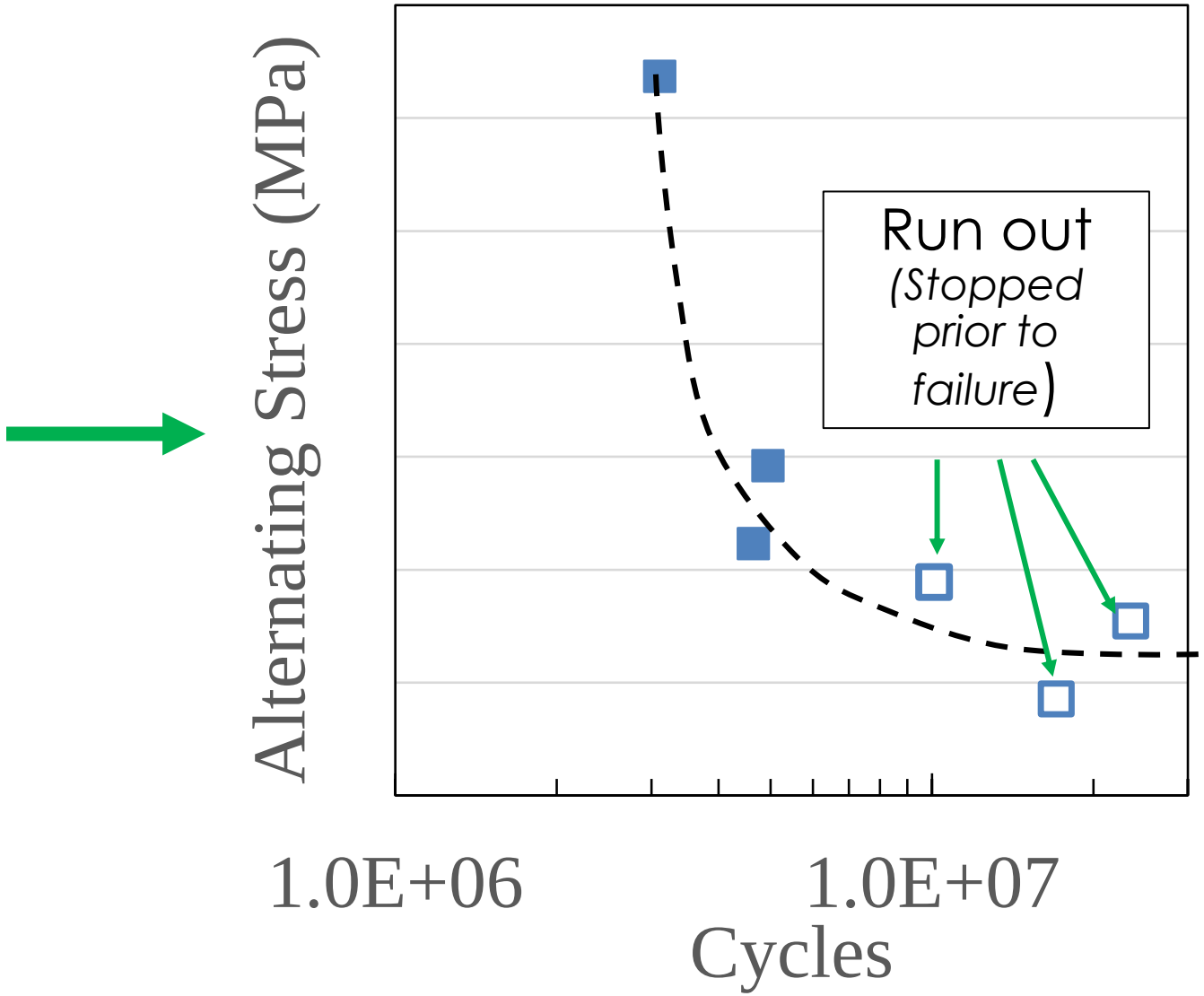
- Condition:
  - as-tempered
  - as-tempered plus aged 500h at 600 °C condition.
- Strength after aging far exceeds existing commercial martensitic steels
- Enables:
  - Higher cylinder pressure
  - Engine downsizing.
- Performed RBF on highest strength alloy





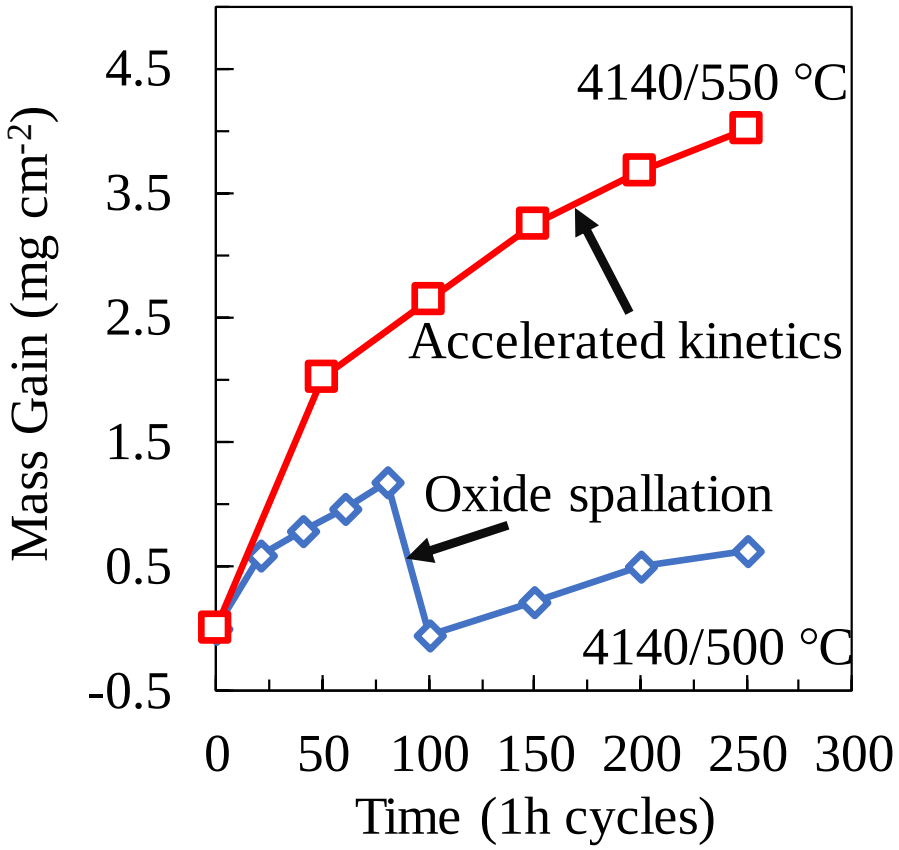
New alloy shows exceptional fatigue strength at 600 °C

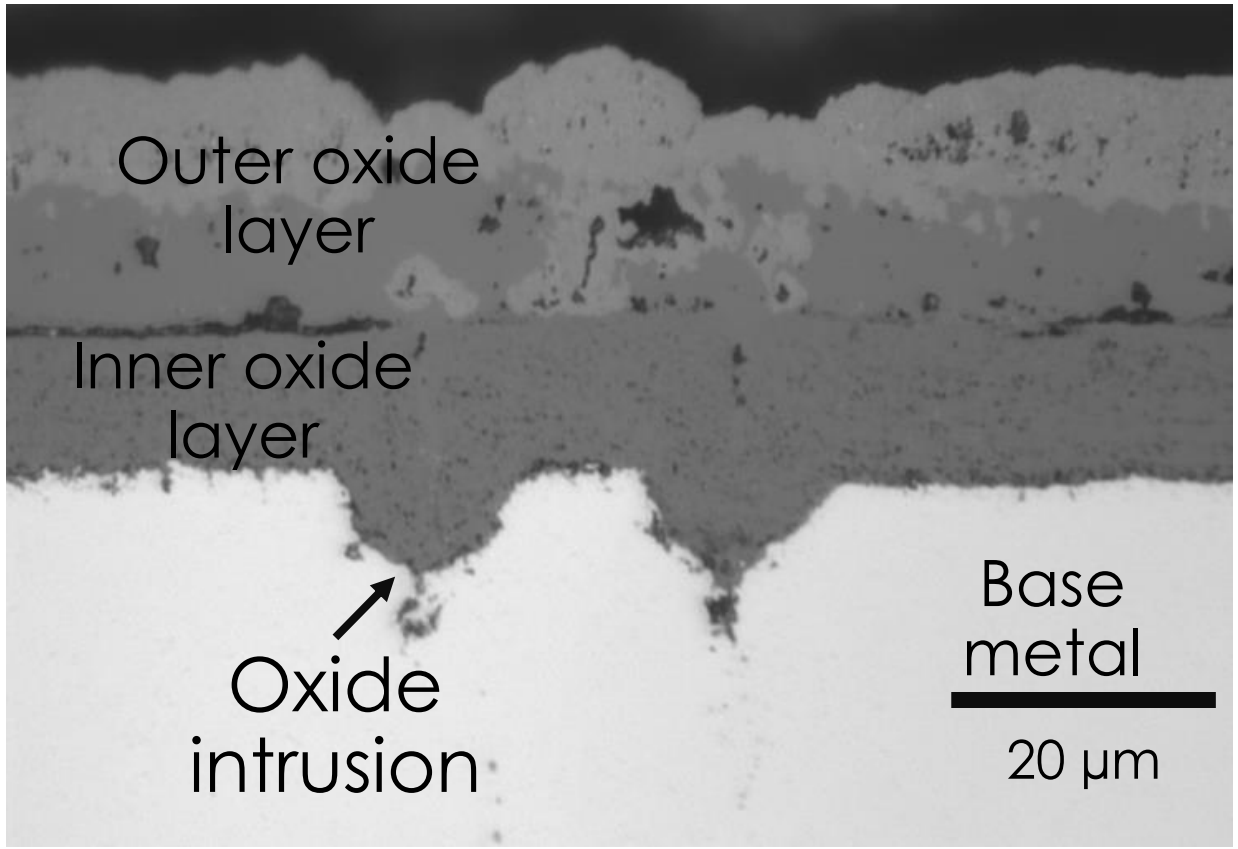
- Rotating beam fatigue testing (5000 RPM)
- Fatigue strength at 600 °C
- Fatigue limit near 0.5 UTS (typical)
- Lab scale heats



4140 Exhibits High Oxidation Mass Gain in Air Plus 10% H_2O

- Developmental alloys (not shown) exhibit superior oxidation kinetics to 4140 at 550 and 600 °C

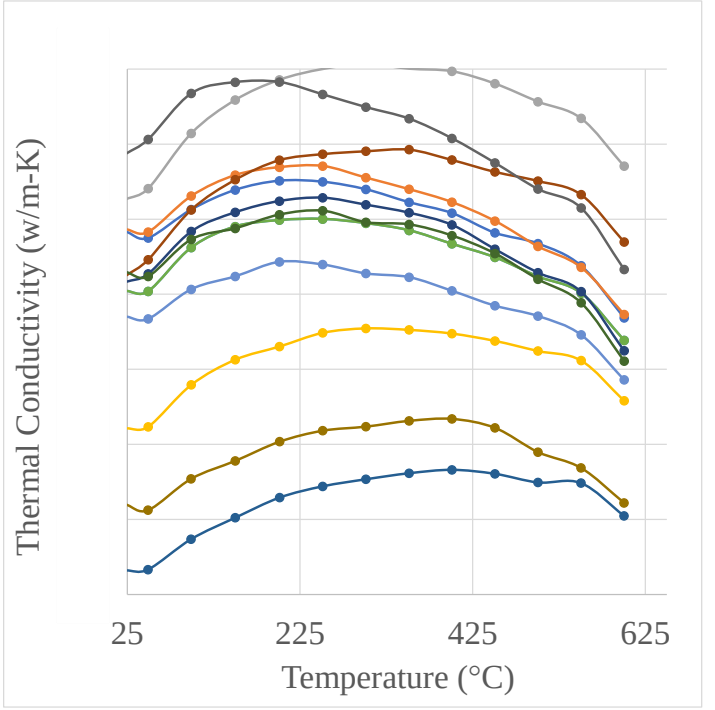


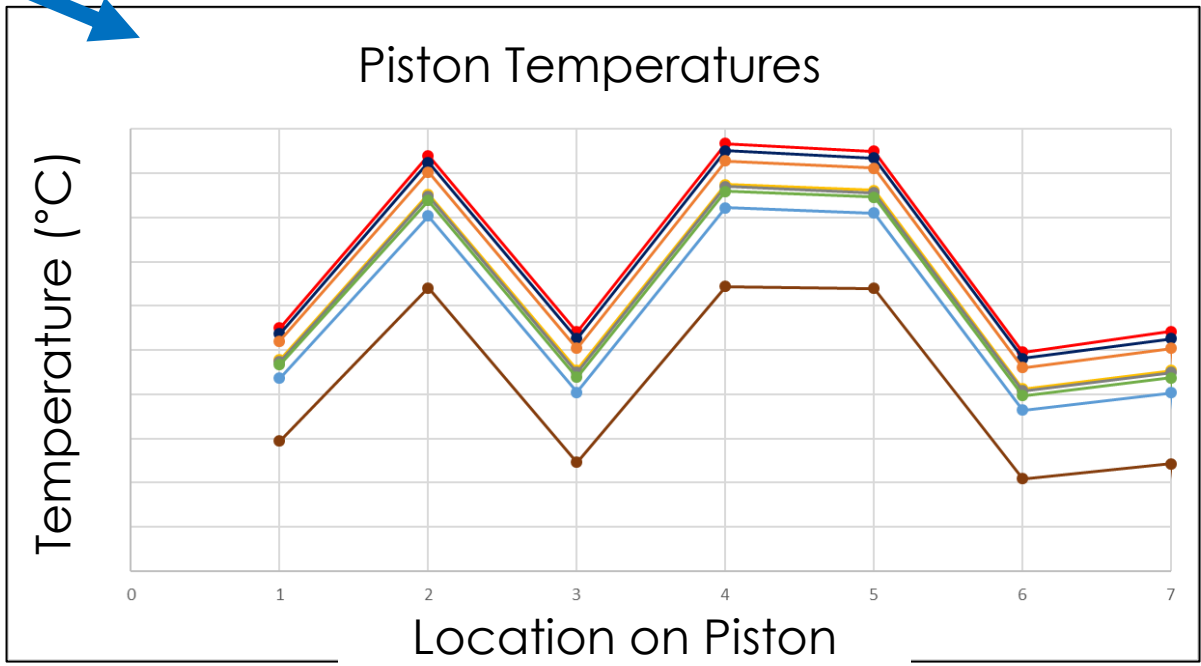


4140: 550°C 250h

Simulation and Analysis Shows Piston Temperature Distribution and Increases in Engine Efficiency

- Thermal property generated for many alloys
- Computational Fluid Dynamics shows higher piston surface temperatures over 4140.
- Simulation indicates brake specific fuel consumption (BSFC) reduced over 4140.
- Deeper analysis ongoing to look at further define efficiency increases.





Responses to Previous years Reviewer's comments

- *Not reviewed last year.*

Remaining Challenges and Barriers

- Scaling up alloy and ensuring steel product quality and properties are similar to that obtained during lab scale processing
- Manufacturing prototype pistons & subsequent engine testing

Collaboration and Coordination

- Cummins and ORNL
- Melting, Processing and Forging Shops
- Partnering with Piston supplier to manufacture prototype pistons

Proposed Future Research for FY22

- FY22:
  - Material scale up
  - Piston fabrication from new alloy
    - Casting
    - Forging
    - Welding
    - Machining
    - Heat treating
  - Engine Testing
  - Post test characterization
  - Analysis-Led Design with materials data generated on component level

Any proposed future work is subject to change based on funding levels

SUMMARY

Developed Novel Cost-Effective Piston Alloy With Improved Properties in 2 Years and in Process of Scaling Up For Engine Testing

- A new alloy has been developed and down selected for piston manufacture and engine testing
- New alloy is cost effective and metallurgical properties were optimized for pistons
- In the process of scaling up to 1500 lbs heat of the alloy for piston prototyping & engine testing